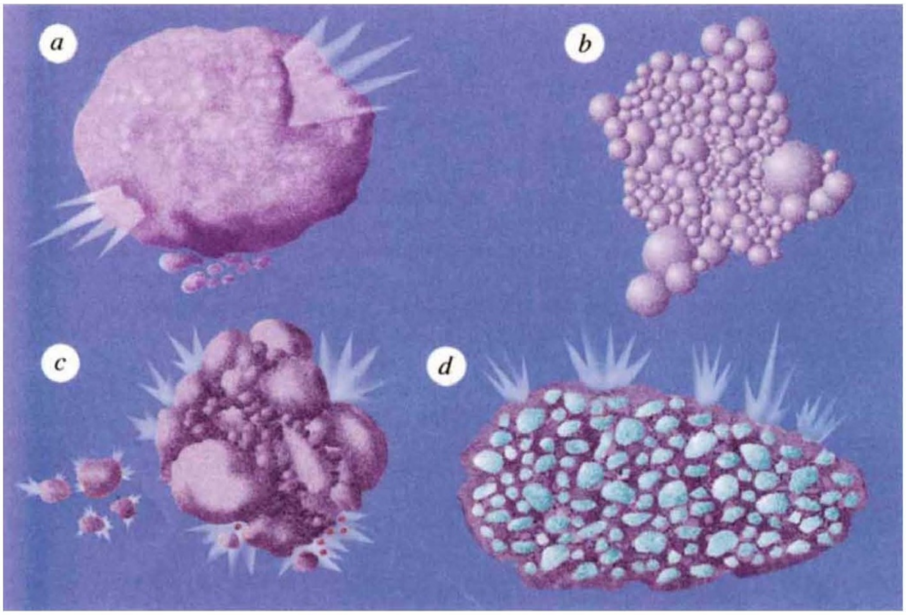
COMET SHOEMAKER–LEVY 9

The Big Fizzle is coming

Paul Weissman

HOW will the fragments of comet Shoemaker–Levy 9 meet their end — with a bang or a whimper? That is the question on everyone's mind as the icy fragments rush towards their cosmic rendezvous with Jupiter, beginning on 16 July. Will Jupiter's atmosphere be torn with massive explosions, each greater than the sum of all the nuclear weapons on Earth, or will it be a giant fizzle? We are about to find out.



Four suggested structures for a comet nucleus, adapted from ref. 10. *a*, The nucleus as an icy conglomerate, *b* a fractal structure, *c* a 'primordial rubble pile', as Asphaug and Benz[1] assume for comet Shoemaker–Levy 9; and *d* the 'icy-glue' model.

Whatever the outcome, the breakup of comet Shoemaker–Levy 9 has provided fresh clues as to the structure of cometary nuclei and their bulk density. One fascinating example is to be found in the paper by Eric Asphaug and Willy Benz on page 120 of this issue[1]. Asphaug and Benz used a high-speed computer workstation to model the breakup of Shoemaker–Levy 9 when it passed within Jupiter's Roche limit two years ago. They assumed that the comet was a 'primordial rubble pile', a collection of hundreds to thousands of dirty snowballs, held together only by their own self-gravity.

This model for comets was independently proposed nearly a decade ago by myself[2], and by Bertram Donn and David Hughes[3], who referred to their idea as the 'fractal model'. An improved description of how such 50-metre-diameter dirty snowballs (or more aptly, frozen mudballs) might form in the primordial solar nebula and then come together to form kilometre-sized nuclei was recently provided by Stuart Weidenschilling[4].

Asphaug and Benz's dynamical simulations show the nucleus of tightly packed snowballs being torn apart by Jupiter's gravity during the close approach, the hundreds or thousands of snowballs stretching into a long column in space. But as the column lengthens and moves away from Jupiter, the individual snowballs begin to clump together because of their own self-gravity. The truly amazing result is that the number of clumps formed appears to be a function of the density of the individual snowballs. At a density less than 0.4 $g\ cm^{-3}$, no clumping occurs; at a density of 2.4 $g\ cm^{-3}$ all the snowballs come back together to form a single body. But at intermediate values, in particular between 0.4 and 0.9 $g\ cm^{-3}$, the snowballs form 15 to 20 clumps. Comet Shoemaker–Levy 9 consisted of 21 individual nuclei when it was discovered last year. (Note: the densities quoted here are those of the individual snowballs; Asphaug and Benz use the bulk density of Shoemaker–Levy 9 before it broke up, which is about 27 per cent less because of the voids between the packed snowballs.)

Results are modified if the original comet nucleus was rotating. Asphaug and Benz's simulations rule out a retrograde rotation, because the snowballs then form a large central clump and smaller outlying clumps; this was not observed for Shoemaker–Levy 9. But if the comet had a prograde rotation, 15–20 clumps are obtained if the density of the snowballs is higher, perhaps 1.3 $g\ cm^{-3}$. Asphaug and Benz's results also suggest that the original comet nucleus was fairly small, at most 1.5 km in diameter, in agreement with work by Scotti and Melosh[5].

Past estimates of the bulk density of cometary nuclei have ranged from 0.1 to 1.3 $g\ cm^{-3}$, based on comparisons of the predicted effects of gases jetting from the sunlit surface of comet Halley with detailed observations of Halley's orbital motion[6–8]. But the many free parameters in such comparisons make the estimates highly uncertain. More recently, meteoriticists have measured the density of microscopic cometary dust grains recovered by U-2 aircraft high in the Earth's atmosphere[9]; these values are typically between 1 and 2 $g\ cm^{-3}$. Asphaug and Benz's results clearly rule out the lower range of values from the estimates of jetting forces, but may be in conflict with some of the higher values from the cometary dust grains.

A question not answered by Asphaug and Benz is whether the individual dirty snowballs in each clump of Shoemaker–Levy 9 have reaccreted into a single body, or whether they are only gravitationally bound dynamical swarms, like bees buzzing around a hive. Several of the clumps have been observed to split, well away from Jupiter's tidal pull, suggesting that within each clump several sub-nuclei may reaccrete, but that a single solid body did not form. Other clumps have dissipated completely with time, suggesting that the snowball swarms don't reaccrete and instead dynamically disperse or sublimate away.

What does this say about the coming impacts on Jupiter? As the clumps approach for their final plunge into the atmosphere at 60 $km\ s^{-1}$, Jupiter's gravity will again pull them apart. Rather than hitting as a single solid body, they will probably come in as an elongated shotgun blast of smaller pellets. Because of Jupiter's rapid rotation, the impact sites will be spread in longitude, like machine gun bullets lacing into a moving target. Each snowball will individually ablate and burn up like a meteor in Jupiter's upper atmosphere. Lacking the momentum and the structural integrity of a single solid body, they will probably not penetrate deeper into the atmosphere, where they might explode with many thousands of megatons of energy.

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Thus the giant impacts will produce a spectacular meteor shower of bright bolides, but not the massive fireball explosions that have been predicted by some researchers. The impacts will be a cosmic fizzle. The cometary meteors may resemble the bolide which exploded harmlessly at 25–34 km altitude over the south Pacific on 1 February this year, with an estimated yield of 15–20 kilotons. The Shoemaker–Levy 9 snowball explosions may be closer to about 30 megatons each, but still far less than the 100,000 megaton explosions that some have predicted.

Nevertheless, Shoemaker–Levy 9's legacy will probably be an improved understanding of the nature of cometary nuclei. It will provide a dramatic confirmation of the primordial rubble pile and fractal models, and will provide the first definitive bounds on the bulk density of cometary nuclei. Then again, maybe it won't. ☐

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EPIDEMIOLOGY

A theory of malaria vaccination

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COULD malaria vaccines eradicate *Plasmodium falciparum* from its stronghold in tropical Africa? While trials of Manuel Patarroyo's Spf66 vaccine[1] are under way in Tanzania[2,3], The Gambia and Thailand, following partial successes in South America[4], Gupta *et al.*[5] have published a stimulating theoretical analysis which suggests that the eradication of malaria by vaccination might be nothing like as difficult as imagined. They also propose that their theory can explain the distribution of different clinical forms of malaria with age[6], and the diversity and dynamics of different parasite strains[7].

The argument about vaccination builds on the logic of the campaign against measles, mumps and rubella. Simple epidemiological theory says that the critical fraction (p) of people to be immunized with a combined vaccine (MMR) to ensure eradication of all three pathogens is determined by the infection that spreads most quickly through a population; that is, by the one with the largest basic case reproduction number, R_0. In the case of MMR, this is measles, with R_0 of around 15, which implies that $p > 1 - 1/R_0 \approx 0.93$. Gupta *et al.*[5] point out that, if a population of malaria parasites consists of a collection of pathogens or strains that have the same properties as common childhood viruses, then vaccine coverage would be determined by the strain with largest R_0, rather than by the R_0 of the whole parasite population. While estimates of the latter have been as high as 100, the former could be much lower.

Analogy

The MMR analogy is a useful one in the context of this theory because it makes clear the defining characteristics of a 'strain' of *P. falciparum*. Strains are not merely antigenic types; rather they must fulfil two particular conditions. First, infection with each strain should generate fully protective, lifelong immunity to that strain. Immunity here means that an individual should be protected against becoming infectious following further exposures to the parasite; protection of this kind may or may not be associated with clinical immunity. Second, there must be no cross-protection between strains.

Are there strains of *P. falciparum* that satisfy these two conditions? Gupta *et al.*[5] have identified the neoantigens (PIESAs) produced on the surface of infected erythrocytes as markers of specific strains. As they acknowledge, the observation that these antigens generate a long-lasting antibody response does not imply durable protective immunity. The only evidence so far that PIESAs stimulate a protective response comes from work by Marsh *et al.*[8] in The Gambia. They found that clinical episodes were fewer, although protection was neither complete nor proven to be durable. They also did not address directly the more relevant but difficult problem of protection against becoming infectious (producing viable gametocytes which are transmissible to mosquitoes), although there was no evidence in cross-sectional data that antibodies to PIESAs prevented parasitaemia.

Although a degree of clinical protection may be associated with strain- or variant-specific antibody responses, these antibody responses may in turn be associated with common or cross-reacting T-cell epitopes that progressively enhance the speed of response to new variants[9]. Gupta and colleagues[5] do actually acknowledge that cross-protection may have a part to play, and they use the idea in their other recent papers to explain why children with cerebral malaria tend to be older than children suffering from severe malarial anaemia[6], and to show how oscillations in malaria incidence could be driven by immunity rather than by fluctuations in external factors, such as mosquito density[7]. Whether or not these explanations are correct is debatable; their relevance here is that they suggest a bigger vaccination problem because cross-protection implies higher effective R_0 values.

Test

One test for cross-protection calculates the expected number of people in different age classes who have been exposed to different strains, assuming independent transmission and some distribution of reproduction numbers across strains. Gupta *et al.*[5] found that expected and observed numbers matched quite closely when five strains studied in Papua New Guinea were each given the same R_0 of about 7. This is a useful numerical demonstration of the way in which R_0 can appear quite small, but it must be seen as no more than illustrative for two reasons. First, if exposure to each strain does not lead to effective protection, then the question of cross-immunity is irrelevant. Second, the supposition that each strain has roughly the same low R_0 is not yet backed by detailed calculations of the incidence rates of a large collection of strains. Parity of R_0 values is not in any case essential for their argument; the strains could have R_0 values which vary from low to very low. Indeed, this is one proposition made[6,10] to explain how insecticide-impregnated bednets can reduce malarial disease without reducing the prevalence of infection.

Many malariologists with control experience will doubt that R_0 in highly endemic areas is as low as Gupta *et al.* suggest. Notwithstanding the effort being devoted to vaccine development, attacking the mosquito population continues to be a mainstay of malaria control. The criterion for eradication by vector control is essentially the same as that for vaccination; p can also be interpreted as the critical fraction by which the mosquito population must be reduced. If $R_0 = 7$, say, then $p > 0.86$. Magesa *et al.*[11] satisfied this condition in a DDT trial in Tanzania, but their success was accompanied by no more than a small reduction in *P. falciparum* incidence, and no detectable reduction in prevalence over the following 12 months. The implication is that R_0 was effectively much higher than 7 in this Tanzanian village.

Even if a *P. falciparum* population does

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